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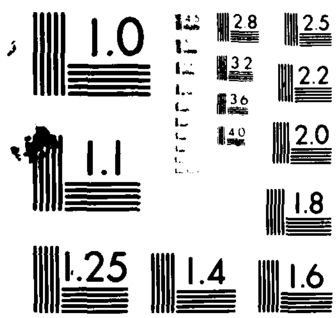

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Galactic Radiation Belts

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It is suggested that electrons trapped in a dipolar field can reproduce some of the observed distributions of emission from extended extragalactic radio sources if the electron pitch-angle distributions are sufficiently anisotropic.

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PREFACE

The author would like to thank M. Schulz and J. B. Blake for reading the original manuscript.

CONTENTS

FIGURES

GALACTIC RADIATION BELTS

Several decades of observations have failed to resolve the problem of the interpretation of extended extragalactic radio sources[1,2]. The majority of current models invoke the ejection of pairs of plasmoids or relativistic electron beams from the parent elliptical galaxy by various mechanisms[3,4,5]. Since these theories generally predict the relative orientations of the rotation, magnetic and radio source axes, the measurement of position angles provides one test of the proposed models [6,7]. However, position angles studies[6,7,8,9,10,11] as a whole have produced ambiguous and sample-dependent results. While several recent analyses[6,7] indicate a preference for radio source alignment along the inferred rotation axes of the optical counterparts, other investigations found random distributions of position angle or bimodal distributions with peaks separated by $\sim 90^{\circ}$ [8,10].

One alternative interpretation of extragalactic radio sources that has received little consideration concerns the possibility that the emission arises from belts of trapped electrons encircling the parent galaxy in the same manner as the Van Allen belts encircle the earth. This idea seems to have been dismissed primarily because of the absence of ring-shaped or toroidal emission patterns in the radio observations.[12] The morphology of synchrotron emission patterns from these hypothetical structures, however, was never investigated in detail.

An integral describing the two-dimensional brightness distribution on the plane of the sky from synchrotron-emitting relativistic electrons trapped in a dipolar magnetic-field shell, was formulated by Ortwein et al.[13] for analysis of the Jovian radio emission. These authors derived their results for an arbitrary dipole-axis orientation angle θ_o with respect to the line of sight and for various degrees of anisotropy of the trapped-electron distribution. The latter was parameterized by the loss-cone angle α_L, which is the smallest populated equatorial pitch angle in the otherwise isotropic particle distribution,and the power law energy spectrum index γ.

While the calculated emission patterns were found to be rather insensitive to the value of γ, they were strongly dependent on both the aspect angle and the loss-cone angle. The emitting shell of electrons assumed one of six different morphologies for various combinations of θ_o and α_L: 1) the solid ellipsoid, sometimes showing complex internal structure, 2) the annulus, 3) the limb-brightened, elongated annulus, which approached in appearance 4) the limb-brightened dumbbell shape, with source axis <u>perpendicular</u> to the dipole axis, 5) the separated double source, with source axis <u>parallel</u> to the dipole axis, and finally 6) the invisible source. Several of these forms are illustrated in Fig. 1.

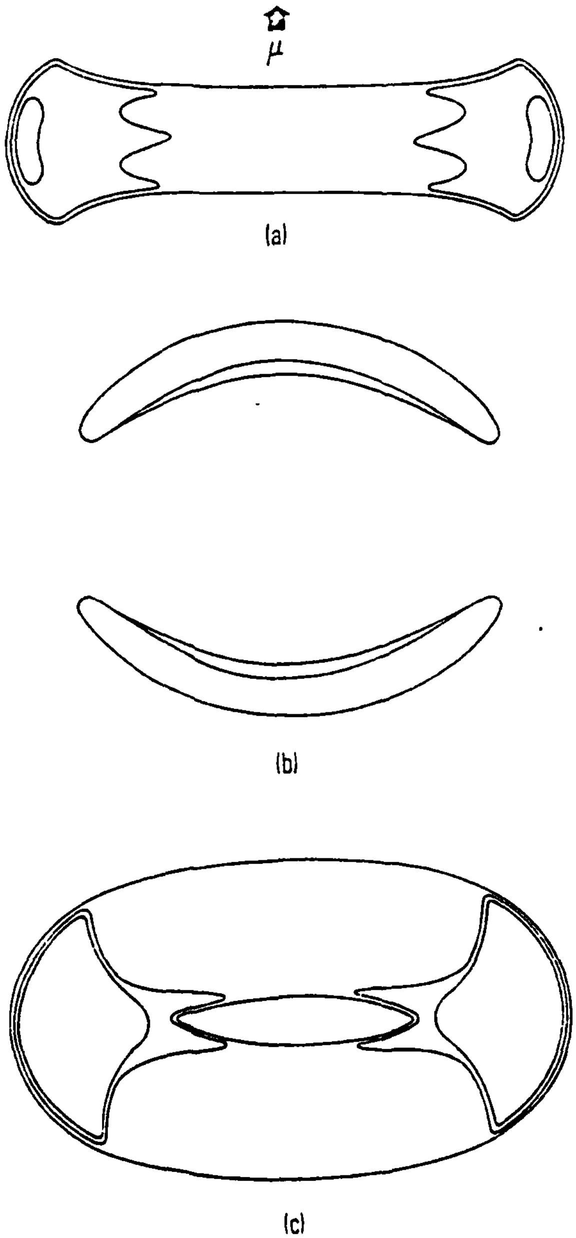

Fig. 1. Examples of Brightness Distributions Produced by Calculations of Synchrotron Emission from Dipolar Shell of Trapped Electrons Using Method Described by Ortwein et al.[13] Dumbbell distribution (a) with source axis perpendicular to dipole moment μ is produced when aspect angle θ_o is 90° (line of sight perpendicular to the dipole axis) and loss cone angle is $\alpha_L = \sin^{-1} 0.8$. A double source with source axis parallel to dipole axis (b) is obtained when $\theta_o = 35°$ and $\sin \alpha_L = 0.8$. The limb-brightened, flattened annulus or torus (c) results from parameters $\theta_o = 60°$ and $\sin \alpha_L = 0.6$. The contour interval is variable. Numerical results can be found in the work of Ortwein et al.[13]

For the present investigation, the numerical integrations described by Ortwein et al.[13] were performed for a large number of aspect angles θ_o between 0^o and 90^o and loss cone angles α_L between 0^o and 90^o. Five-degree intervals were taken in aspect angle θ_o and sin α_L was incremented by 0.05. The electron spectral index γ was set equal to the nominal value of 1.5, which is the galactic cosmic-ray index[14]. Two-dimensional plots of the intensity were generated for each case. These were then categorized according to morphological class as defined by the six types described above.

Figure 2 shows how the morphology of the brightness pattern varies as a function of aspect angle and electron pitch angle anisotropy. In nature, the dipole axes will be isotropically distributed. However, all loss-cone angles may not occur. In particular, the results given in Fig. 2 indicate that if large loss cones (sin $\alpha_L > 0.8$) are prevalent, the observed distribution of source morphologies will be practically equivalent to what has been found in some of the data analyses. These thin disk-like populations of gyrating electrons produce emission patterns that are virtually undetectable or double with the radio source axis either parallel or perpendicular to the dipole axis of the parent galaxy. (The limb-brightened annuli are likely to appear as doubles connected by "bridges" of emission).

Of course, actual galactic radiation belts would be composed of a distribution of nonuniformly emitting shells, thus altering the emission patterns somewhat. For example, it would not be surprising to find (under circumstances of nonuniform sources, sinks, and field geometry)

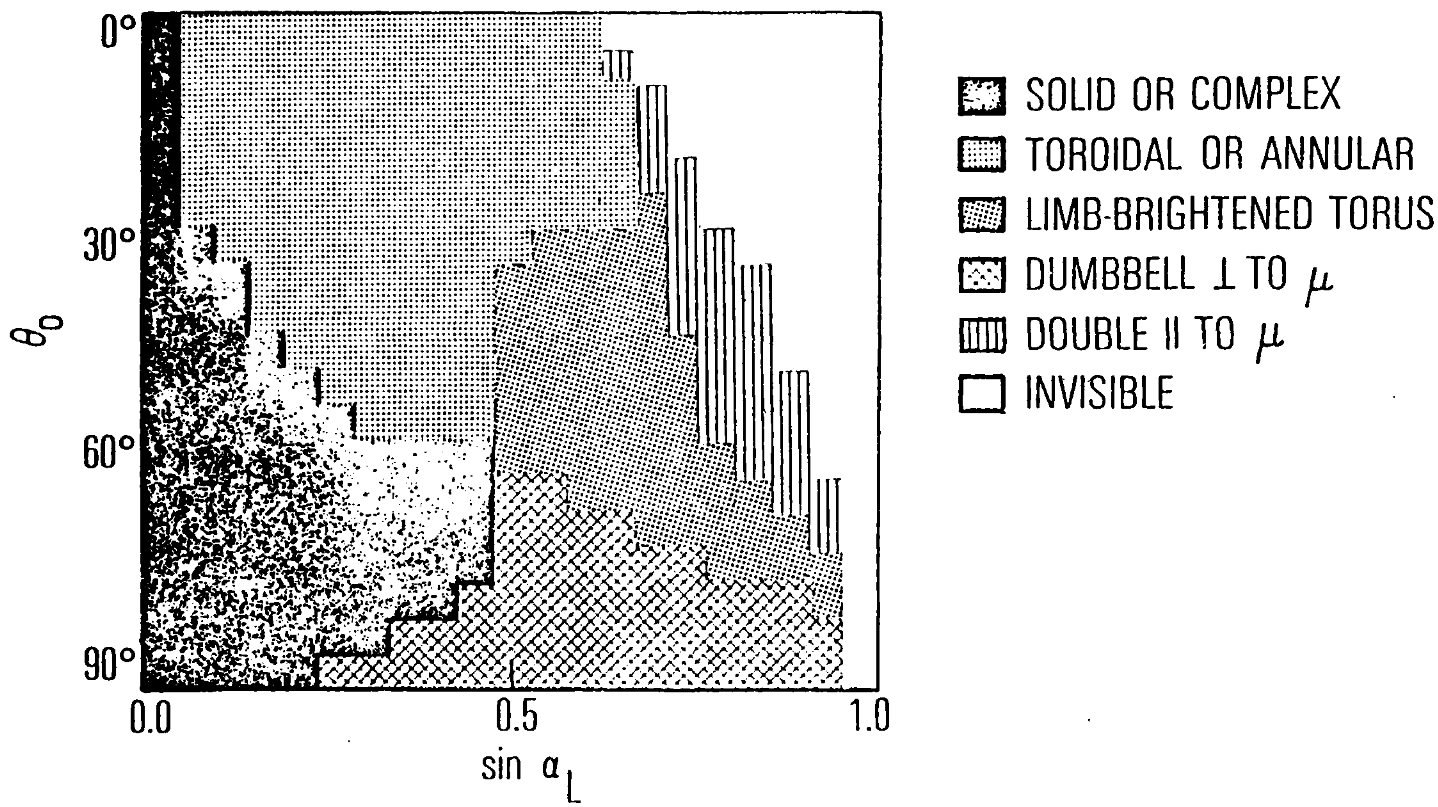

Fig. 2. Distribution of Source Morphologies for All Values of Aspect Angle θ_o and Loss-Cone Angle α_L.

cases of multiple belts which appear as nearly collinear paired sources. Also, galaxies with minimum-B surfaces that are warped by non-dipolar field components[15] may show an anomalous displacement between the rotation and magnetic axes, as well as asymmetric trapping regions. Moreover, a galactic wind[24] or local intergalactic material can further distort the configuration of trapped electrons. Figure 3, which compares the brightness distributions and inferred magnetic field geometries of several extra-galactic radio sources[16] with the Jovian radiation-belt source,[17] suggests an intriguing similarity.

The related questions of why galactic radiation belts should exist at all and why they would be populated by electrons with such a highly anisotropic pitch angle distribution lead to several speculations. Parker[18] demonstrated that the magnetic field of our own galaxy could be attributed to dynamo activity. It is well known[19] that dipolar components are preferentially excited in dynamos and dominate the field at large distances from the dynamo center. It is also well known that galaxies contain sources of energetic particles, the cosmic rays. Various scattering mechanisms and propagation effects[20,21] can cause particles originating in the galaxy to become trapped in a surrounding dipolar field which is effectively a highly organized cosmic-ray halo. In fact, the cosmic ray spectrum observed in earth's vicinity could produce the observed radio source spectra.[22] Finally, Schulz[23] pointed out that both synchrotron losses and radial diffusion processes in radiation belt configurations naturally lead to pitch angle distributions that are strongly peaked at an equatorial pitch angle of 90°.

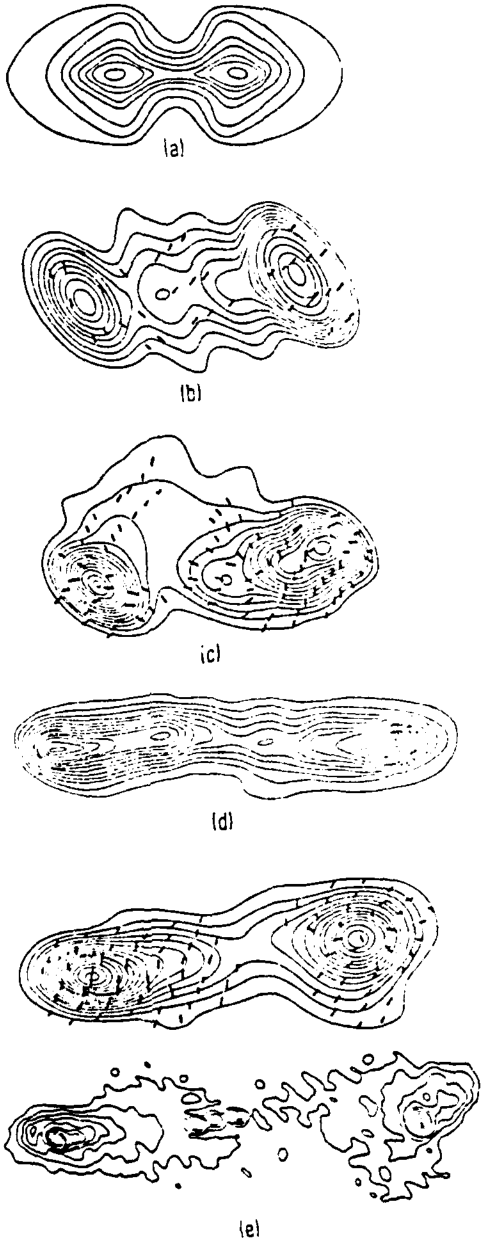

Fig. 3. Selection of Observed Radio-Source Brightness Distributions at Various Resolutions: (a) Jupiter[17] at 10.4-cm wavelength; (b) 3C234[16] at 1.4 GHz (21 cm); (c) 3C382[16] at 1.4 GHz; (d) 3C452[1] at 1.4 GHz; (e) 3C219[16] at 1.4 GHz (top) and at 2.7 GHz (bottom). Dashes show the direction of magnetic field in the sources as inferred from polarization measurements.

Many peripheral points of interest can be found in analogies with other radiation belts in nature.[23,25] The perpendicular sources may show evidence of the gradient-curvature drift of the trapped particles around the parent galaxy. This azimuthal drift would cause opposite Doppler shifts of the synchrotron radiation from the two extremities of the source. Magnetic storms, analogous to those which accelerate particles in Earth's environment,[26] may have their counterparts in galactic magnetospheres. The variation of the radio sources with time will be determined by the competition between particle sources and synchrotron losses, and also by changes in magnetic field geometry. Some 'tailed' radio sources have already been compared to the earth's magnetosphere[27,28].

These speculations notwithstanding, the calculations described above suggest that electrons trapped in a dipolar magnetic field can reproduce some of the observed distributions of emission from extended extragalactic radio sources, including the absence of toroidal configurations, if the electron pitch angle distributions are sufficiently anisotropic.

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